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Aerial Additive Building Manufacturing of 3D printed Cementitious Structures

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ABSTRACT

This paper describes and evaluates a cementitious paste solution for the first aerial additive building manufacturing system, developed to create and repair civil engineering structures in-situ using materials 3D extrusion-printed by aerial robots. Cementitious pastes without aggregate were created to determine their suitability for a powered deposition device light enough to be carried by an aerial robot. Mixes of varying water/cement ratio and plasticiser content, along with admixtures, were manufactured and the curing of the pastes was monitored using a cone penetrometer. Flexural test specimens were manufactured using the deposition device and moulded compressive test specimens were created by hand. Strengths in excess of 40 MPa (compressive) and 2.74 MPa (flexural) were achieved. The optimal mix for extrudability had a water/cement ratio of 0.33 with 1.5% superplasticiser by weight of cement added. This mix remained workable for an hour without additional chemical retardation. The autonomous deposition device successfully imported and extruded workable cementitious paste, demonstrating the structural and operational feasibility of cementitious pastes for autonomous 3D extrusion-printing using aerial robots.

1. INTRODUCTION AND REVIEW

The Aerial Additive Building Manufacturing (ABM) project is researching a construction system of coordinated, swarming aerial robots, each carrying a lightweight 3D extrusion-printing device, depositing a material with a suitable combination of workability and buildability to create or repair structures in-situ [1]. The feasibility of aerial robots being able to 3D print polyurethane foam during controlled flight has been demonstrated by the Aerial Robotics Laboratory of Imperial College, London [2].

Traditionally, the construction industry has extensively used subtractive or formative building methods [3]. Additive Manufacturing (AM) can offer advantages over traditional practise. By building layer by layer, only the material specifically required is deposited, thus reducing wastage. Less labour is required, reducing costs, delays and the risk of accidents. When an integrated approach involving services is undertaken, there are potential cost benefits to a project, despite potentially high equipment outlays or raw material costs [3]. A homogeneous building reduces detailing and remedial works. AM also offers bespoke design at no extra cost [3], as a complex design takes no longer to 3D print than a simple design.

The development of AM in construction has been slow in comparison to the automotive and aerospace sectors [3] and the technology is still essentially in its infancy [4]. Currently, aerial robot use in the construction sector focuses on surveillance, inspection and costing work [5], rather than AM.

Current research into 3D printing cementitious materials involves ground based systems [6,7,4]. AM methods include Contour Crafting, developed at the University of Southern California, USA [8,9], concrete printing developed at Loughborough University, UK [3,6,10,11] and D-shape printing, developed by Enrico Dini of D-shape Enterprises [12]. Concrete printing and contour crafting involve the fused deposition modelling (FDM) principle of depositing liquid material one layer at a time. FDM is a suitable method for autonomous aerial 3D printing of a cementitious structure. The properties of the wet, freshly extruded concrete are critical [6]. Concrete printing produces a characteristic ribbed effect, whereas Contour crafting uses top and side trowels (on the external face), providing a smoother finish. The D-shape method involves depositing a binding solution into a powder bed of material to solidify the powder [12] and is a less appropriate method in the context of the Aerial ABM project.

There are four primary characteristics of wet cementitious material: 'Pumpability' - the ease of material movement through a deposition system, 'Extrudability', (or 'Printability') - the level of ease and reliability with which a material may be deposited through a nozzle, 'Buildability' - the ability of wet extruded material to resist deformation under load (a term describing the extent to which layers can support themselves and subsequent layers) and 'Open time' - the time period within which the above three properties remain consistent [6,10,11]. The more general term 'workability' may be taken to encompass pumpability and extrudability.

There is a trade-off between workability and buildability (strength and stiffness) [12]. Slower curing mixes possess lower stiffness and initial strength - reducing buildability - but are more geometrically forgiving. By maintaining workability, they keep surfaces chemically active and reduce dependency on time between layer deposition [4]. To achieve a balance between workability and buildability, a superplasticiser can allow a low water/cement (w/c) ratio, thus increasing early age strength and prolonging workability. Previous cementitious printing experiments have used a water/binder ratio in the region of 0.28, adding 0.5% (by weight of cement) of superplasticiser [10,11] and featured the development of a model concerning the determination of an optimal time between the depositions of the layers using an 0.41 w/c ratio with 0.3% superplasticiser [13].

This paper focuses upon the initial stage of the Aerial ABM project's cementitious material investigations. A cementitious paste without aggregate, which may be drawn up and extruded by an autonomous deposition device light enough to be carried by an aerial robot, has been developed. The emphasis at this initial stage is on workability, however buildability will be considered.

2. MATERIALS AND METHODOLOGY

This study encompasses the following experimental phases:

- Determination of a workable cement paste mix suitable for the autonomous deposition device, combining the variables of w/c ratio and plasticiser % by weight (wt.) of cement. No aggregate was used.
- Cone penetrometer tests to determine the time period in which the paste remains fully workable ('open time'). The effects of an accelerating admixture and the requirement for retardation were assessed.
- Compressive and flexural tests of the most appropriate cured cementitious paste mix.

The materials used were Dragon Alfa CEM I 42.5 R Portland cement with a mean particle size of 5-30 micrometres, MasterGlenium ACE 499 polycarboxylate ether-based superplasticiser and a laboratory-made accelerating solution consisting of 1:1 aluminium lactate and diethanolamine.

The deposition device (Figure 1) was developed for integration into a 3DR ArduCopter Quad aerial robot [2,14]. The device employed a miniature 6V DC brushed motor with a 986:1 metal gearbox powered in this study by a PL155 Aim TTI bench supply. Dual syringes were designed to accommodate liquid-component polymeric materials [2,14] and both syringes' plungers were actuated simultaneously by a 3mm diameter leadscrew mechanism which translated the rotation of the motor's shaft to linear motion. Currently, aerial robot carrying capacity is 0.6 kg – this accommodates two BD Plastipak 60ml, 26mm diameter barrel concentric luer lock syringes replete with cement paste. An 8mm opening, drilled into the luer lock, formed an 8mm internal diameter nozzle for extrusion.

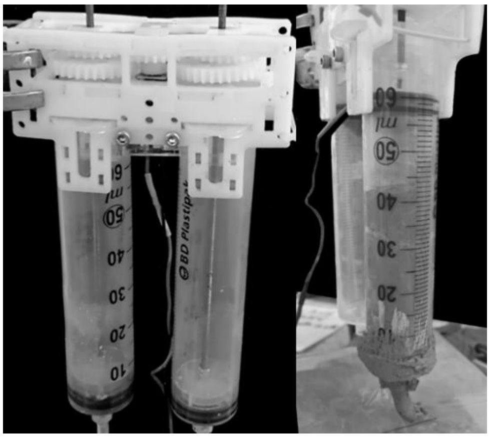

Figure 1. The autonomous syringe deposition device, suitable for carriage by an aerial robot.

The device was tested with a range of cementitious mixes, in which the variables of w/c ratio and added superplasticiser were altered in the range of 0.31-0.41 and 0-2.5% by weight (wt.) of cement respectively. The workability of the most appropriate cement paste mix for the syringe device was then tested using a cone penetrometer to assess the effects of acceleration. Three concentrations of the accelerating solution were used - 0.10%, 0.15% and 0.20% by weight of cement. The cone penetrometer accurately measured to a maximum drop of 25mm.

Strength tests were conducted on a 50 kN Instron Universal 2630-120/305632 machine. Specimens consisted of the most appropriate mix for deposition device workability. 18mm diameter x 37mm high compressive specimens were manufactured by hand-mixing a large quantity of paste and pouring into cylindrical moulds. Specimens were created in two batches: batch 1 consisted of just the cementitious paste mix and batch 2 added 0.15% (by wt. of cement) accelerator to the mix. Compressive strength was tested at 1, 7 and 28 days. For both batches on all days, six specimens were tested to failure and the mean strength was calculated. Flexural strength test specimens were autonomously drawn-up and extruded through the 8mm nozzle to a length of 70mm ±5mm and tested in three-point bending with cylindrical supports placed 55mm apart at the centre. Flexural strength was tested at 28 days. The time taken and current required to draw-up and extrude the paste was monitored.

3. RESULTS AND DISCUSSION

The results of the workability of the w/c ratio and superplasticiser test mixes used with the syringe deposition device are shown in Table 1. Mixes aimed to minimise the w/c ratio to improve strength, without using excessive plasticiser thus risking filament deformation [11]. Based upon this and the ease of extrusion, a w/c ratio of 0.33 with a superplasticiser dosage of 1.5% by wt. of cement was selected as the most appropriate mix for an 8mm diameter nozzle syringe powered by the deposition device.

Table 1. Experimental matrix showing Water/ Cement ratio and superplasticiser by % weight of cement. Key:
✓ = good workability, successful draw-up and extrusion.
× = excessive workability, too runny and an absence of strength upon deposition leading to excessive deformation.
☒ = low workability, material would not flow or experienced segregation of water and cement in the syringe.
- = mix design deemed unsuitable and not attempted.

Water/ Cement ratio	Superplasticiser: % weight of cement				
	0	1.0	1.5	2.0	2.5
0.31	-	-	-	-	☒
0.32	-	-	☒	✓	✓
0.33	-	-	$\boxed{✓}$	-	-
0.34	-	-	×	×	-
0.38	-	☒	-	×	-
0.39	-	✓	-	-	-
0.40	✓	-	-	-	-
0.41	×	-	-	-	-

By maintaining 5.95V on the syringe deposition device power supply, it required 18 minutes to draw up 60 ml of cement paste and 18 minutes to extrude. During this time, the optimal cement paste mix maintained pumpability and extrudability. The required current was 28 mA ±8 mA, resulting in a power requirement ≅ 0.17 Watts to draw-up and extrude 60 ml.

With the cone penetration tests, it was discovered that the optimal mix was still workable at 60 minutes, but at 90 minutes workability was compromised to the extent that the paste did not possess extrudability or pumpability. At 60 minutes, the cone penetrated 16.1mm, by 90 minutes penetration was 15.3mm. Therefore, an average of 15.7mm was taken as a threshold for extrudability (Figure 2) which gives an open time of 75 minutes – if the cone cannot penetrate deeper than this threshold, the paste is deemed no longer extrudable and workability is lost.

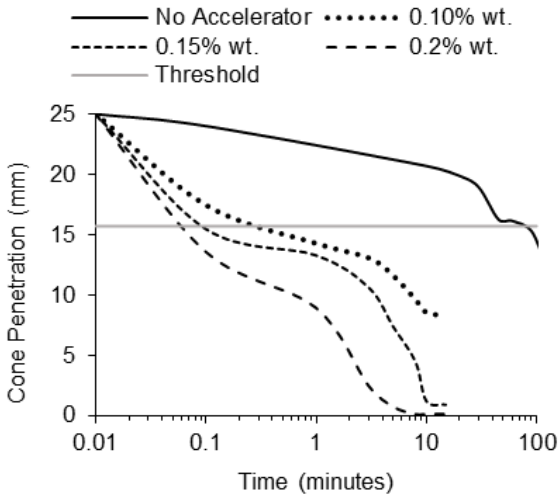

Figure 2. Cone penetration of the 0.33 w/c ratio, 1.5% wt. of cement superplasticiser mix with added 1:1 aluminium lactate and diethanolamine accelerator by 0.10, 0.15 and 0.20 % wt. of cement. The x-axis has a logarithmic scale.

It can be seen from Figure 2 that the 1:1 aluminium lactate and diethanolamine solution is an effective accelerator and currently could not be used with the deposition device in its current dual-syringe, single motor form due to compromised workability taking place within one minute. However, there is scope to reduce the dosage or modify the device, allowing independent control over each syringe. Modification would allow the addition of accelerator to the paste immediately prior to extrusion, thus enhancing buildability by rapid strength increase. This would enable support of self-weight and the ability to support subsequent layers deposited in quick succession. As the paste, without accelerator, has an open time in excess of an hour, there is no immediate requirement for retarding admixtures.

The compressive strengths of 18mm diameter x 37mm cylindrical specimens are shown in Figure 3. The aluminium lactate and diethanolamine accelerating solution increased the strength of the paste at 1 day and 7 days. By 28 days, the specimens without the added accelerator ultimately proved stronger, but the compressive strength of the accelerated specimens remained in excess of 40 MPa. The mean flexural strength of the syringe-extruded, non-accelerated specimens tested at 28 days was 2.75 MPa. The compressive and flexural strength of the cementitious paste was therefore competitive with that of Portland cement-based concrete.

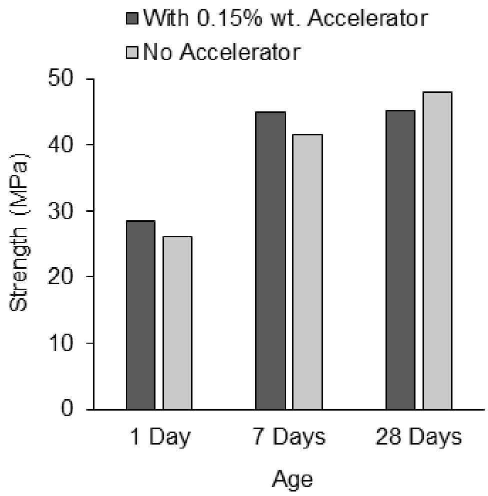

Figure 3. Compressive strength of the chosen cement mix.

The strengths demonstrate that a cement paste, suitable for an autonomous extrusion device, is viable as a structural material. In common with unreinforced concrete, failure in flexure is brittle. Therefore, to explore the material further as a homogeneous 3D printable material would involve adding fibres to the paste, introducing ductility and further improving tensile properties. Polypropylene, steel, alkali resistant glass and carbon fibres will be investigated. Additionally, the buildability of the paste would be enhanced with the addition of fine aggregate.

4. CONCLUSIONS

Additive Manufacturing (AM) offers many improvements over traditional construction methods and adopting an aerial approach frees AM from ground-based design and logistical restrictions. The most suitable cementitious paste mix for the autonomous syringe deposition device, without aggregate, was 0.33 w/c ratio and 1.5% (wt. cement) superplasticiser. This mix possessed an open time of approximately 75 minutes, therefore a retarding admixture was not required. Aluminium lactate and diethanolamine form a potent accelerator. Further investigation is necessary as early shear strength, before hardening by hydration, will provide buildability and reduce the time required between layer depositions. Although the accelerator reduced 28-day compressive strength, it remained in excess of 40 MPa. Flexural failure was brittle – investigation into the addition of fibres to provide ductility will progress the realisation of a paste suitable for AM purposes. Further work will encompass rheological tests of the cementitious paste and development of buildability.

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